Quality Control of Chloride Diffusivity of the High Durable Concrete for Approaching Road of Incheon Bridge

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Abstract: *Fick's first and Fick's second law of diffusion may be applied to quantify the chloride ingress in the steady-state and non-steady-state, respectively. But these methods need a long time, and also it is significantly difficult to estimate the diffusion coefficient in the non-steady-state situation like the existing concrete structures. Therefore, the objectivity of this study is to establish a efficient, convenient accelerated laboratory test methods of the diffusion characteristics of concrete, indirectly.*

In this study, 4 accelerated laboratory test methods were selected according to the domestic and foreign test specifications and applied to the same ages of concrete specimens.

Test results has indicated that the coefficient by ASTM C 1202 has shown the only relative differences of the different mix proportions and the diffusion coefficient in steady-state is one tenth of that in non-steady-state. Also, diffusion coefficient by immersion test is similar to that by NT Build 492. Based on the above results, the test method and criteria for quality control and maintenance of chloride attacks has been established.

Keywords: *Fick's first law of diffusion, Fick's second law of diffusion, steady-state, non-steady-state, diffusion characteristics of concrete, quality control*

1. INTRODUCTRON

Corrosion induced primarily by chloride ingress and diffusion, deteriorates concrete structures exposed to aggressive agents, such as chloride, significantly. Therefore, chloride attack should be included to estimate durability and design of concrete structures.

JSCE method of Japan, ACI method (Life 365) and Duracrete method in Europe have been introduced to us to design concrete structures that are vulnerable to chloride attack. Diffusion coefficient is one of the primary parameter to design durable concrete structures. JSCE recommends that the constant derived from experimental data of the existing concrete structures as diffusion coefficient. In ACI and Duracrete models, time dependency is included and experimental data from the previous research results is used.

As stated above, it is difficult to compare the diffusion coefficients in every model, directly because data based on the different condition are used. Therefore, unique model for diffusion coefficient should be established to estimate life span of concrete structures including chloride attacks.

In this study, to control quality of durable concrete against chloride attack in fields, the optimum test method has been selected and diffusion characteristics has been compared at different ages through the comparison and analysis of the models and test methods specified in other countries.

2. ACCELERATED DIFFUSION TEST METHOD USING POTENTIAL GRADIENT

Generally, mechanisms of the ingress of deleterious material into concrete are classified into diffusion due to concentration of the diffusing substance, permeation by pressure head, and capillary suction due to surface tension acting in capillaries.

Diffusion is that transfer of mass by random motion of free molecules or ions in the pore solution resulting in a net flow from regions of higher concentration to regions of lower concentration of the diffusing substance. Diffusion may depend strongly on the local concentration of free ions or molecules, location, time, and temperature. Fick's first law and Fick's second law of diffusion are used in the steady-state and non-steady-state, respectively to predict the diffusion coefficients. Because, it is significantly difficult to predict the diffusion coefficient in the non-steady-state situation like the existing concrete structures, usually, accelerated laboratory test methods of the diffusion characteristics of concrete are used, indirectly.

Recent researches have been focused to electro-chemical theory by inducing and accelerating electrical migration of ions due to potentials, because to estimate the diffusion characteristics of concrete is time consuming and effortful. Transport of ions in electrolytes due to the migration component arising from potential gradients as the driving force is given by the Nernst-Planck equation.

$$J = -D\frac{dC}{dx} - \frac{zF}{RT}DC\frac{dE}{dx} + V_e \text{ -------- (1)}$$

(Total flux = diffusion + migration + convection)

Where,
- J = mass flux (g/m^2s),
- D = diffusion coefficient (m^2/s),
- C = concentration (g/m^3),
- x = distance (m),
- Z = electrical charge,
- F = Faraday constant (J/V·mol)
- R = gas constant (J/mol·K)
- T = absolute temperature (K)
- E = electrical potential (V)
- V_e = velocity solution (m/s)

This general equation states that the diffusion due to the difference in concentration, the migration component arising from potential gradients, and convection of ions due to electrolyte movement. The diffusion coefficient from the accelerated potential gradient may be calculated assuming a stationary flow of ions and provided there is no convection of ions due to electrolyte movement. In this study, ASTM C 1202 which is a test method of ability to resist rapid penetration of chloride ion, NT Build 355, 433, and 492 are conducted as accelerated test methods, as shown in Table 1.

3. EXPERIMENTAL WORKS

3.1 Mix Proportions

These concrete mix proportions used in this study will be applied to concrete bridge structures exposed to chloride attack. Mix proportions used are detailed in Table 2. Only Ordinary Portland Cement

(OPC) was used in Mix A, while the various percentages of ground granulated blast furnace slag (SG) were used in the rest of mixes. Unit water content in the range of 152~175 kg/m^3 and air content of 4.5~5.0 % were also used.

Table 1 Accelerating test methods and conditions for assessing chloride ions diffusivity

Test method	Measuring item	Required time	Electrolyte solution	Applied voltage	Equation
ASTM C 1202 Standard test method for electrical indication of concrete's ability to Resist chloride ion penetration[1)] **(KS F 2711)**	Total passed charge	6 hours	(+) 0.3N NaOH (-) 3.0% NaCl	60V	$Q_{tatol} = 900 \cdot (I_0 + 2I_{30} + \sim + 2I_{300} + I_{360})$
NT Build 492 Chloride migration coefficient from non-steady-state migration experiments[2)]	Penetration depth	24～48 hours	(+) 0.3N NaOH (-) 10.0% NaCl	10~60V	$D = \frac{RT}{zFE} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t}$
NT Build 355 Chloride diffusion coefficient from migration cell experiments [3)]	Concentrati on. Increase rate	1～2 months	(+) 0.3N NaOH (-) 5.0% NaCl	12V	$D = \frac{JRTL}{z_{cl} F \Delta E C_1}$
NT Build 443 Accelerated chloride penetration[4)]	Penetration profile	Minimum 1 months	2.8N NaCl Solution	-	$C(x,t) = C_o \cdot erf(x / \sqrt{4 \cdot D \cdot t})$

Table 2 Mix proportions of concrete

Type	Design compressive strength (MPa)	Air content (%)	Unit water content (kg/m^3)	Unit binder content (kg/m^3)		W/bm (%)	Remark
				OPC	SG		
A	40	4.5	175	500	-	35	OPC
B	35	4.5	169	211	211	40	SG50
C	40	5.0	169	370	158	32	SG30
D	35	4.5	160	216	216	37	SG50
E	35	4.5	152	213	213	36	SG50

3.2 Test Methods

3.2.1 ASTM C 1202

Diffusion cell is composed as shown in Fig. 1. A potential of 60 V is applied to the both ends of concrete specimen for 6 hours to accelerate the velocity of migration of chloride ions. Ability to resist chloride ion penetration can be calculated from the total Coulombs.

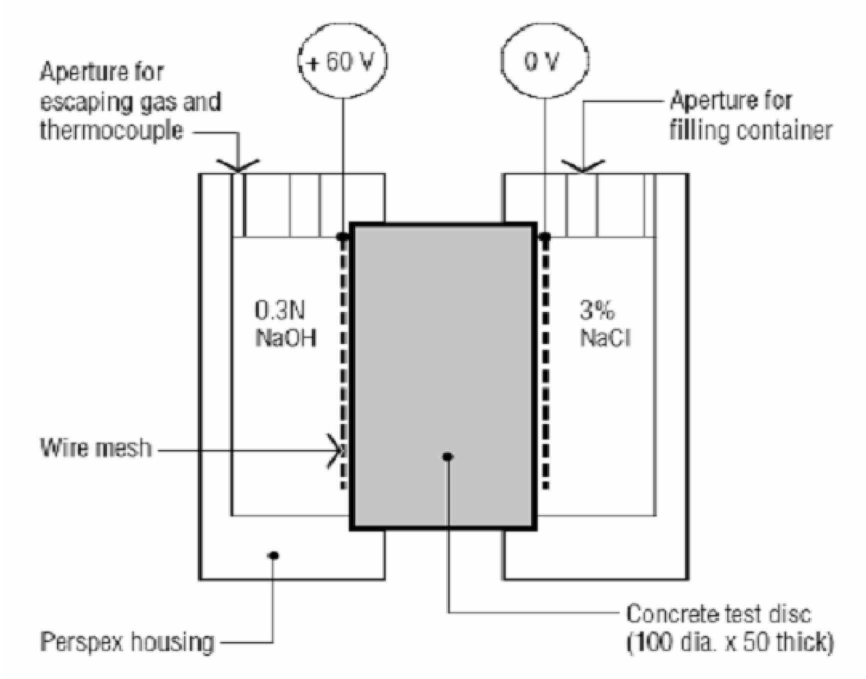

Fig. 1 ASTM C 1202 test arrangement

3.2.2 NT Build 355

Experimental arrangement is shown in Fig. 2. A potential of 12 V is applied across the concrete specimen to accelerate the velocity of migration of chloride ions. When a steady state chloride flow is reached, that is, $\Delta C_2/\Delta t$ becomes constant (Fig. 3), the diffusion coefficient can be decided.

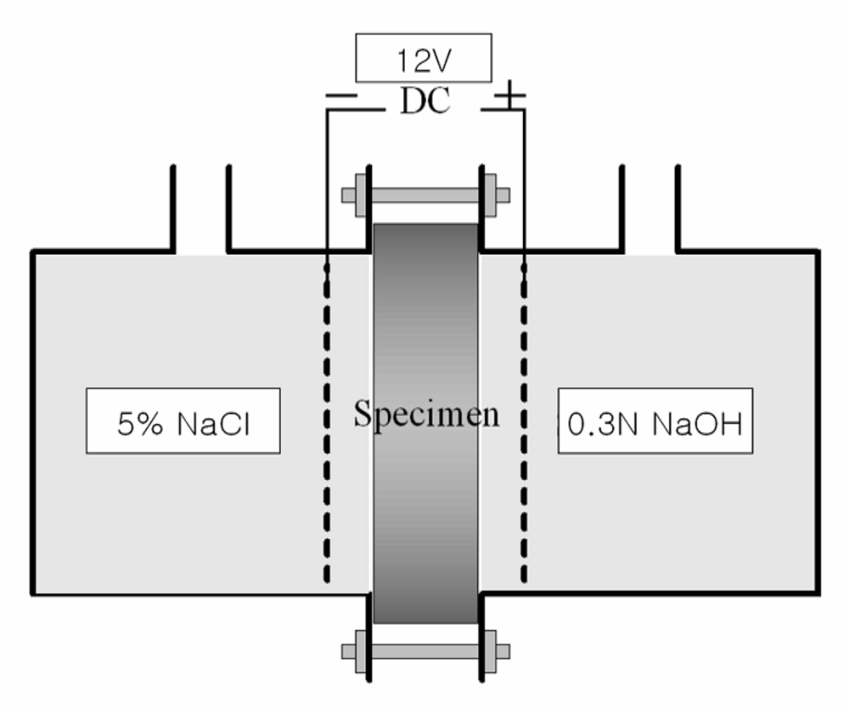

Fig. 2 NT Build 355 test arrangement

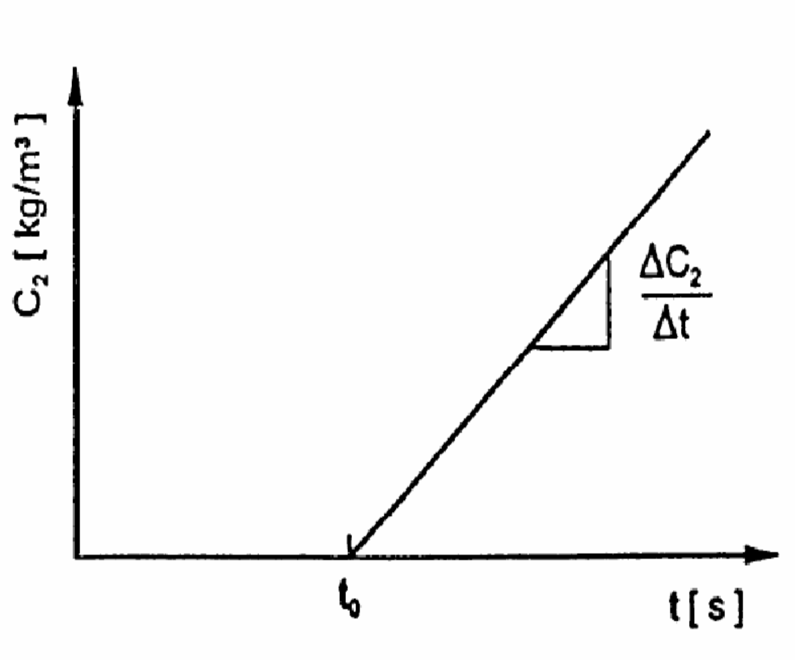

Fig. 3 Concentration rate in steady-state

3.2.3 NT Build 443

In order to shorten the test period, the conventional immersion test has been modified by increasing the chloride concentration or elevating the exposure temperature. This immersion test usually involves the following procedures. All surfaces of a concrete specimen except one are sealed to prevent multi-directional penetration. The concrete specimen is immersed in a solution containing chloride ions. After a certain period of immersion, the chloride profile is measured by grinding the specimen successively from the exposed surface. Test set-up and the chloride profile are shown in Fig. 4.

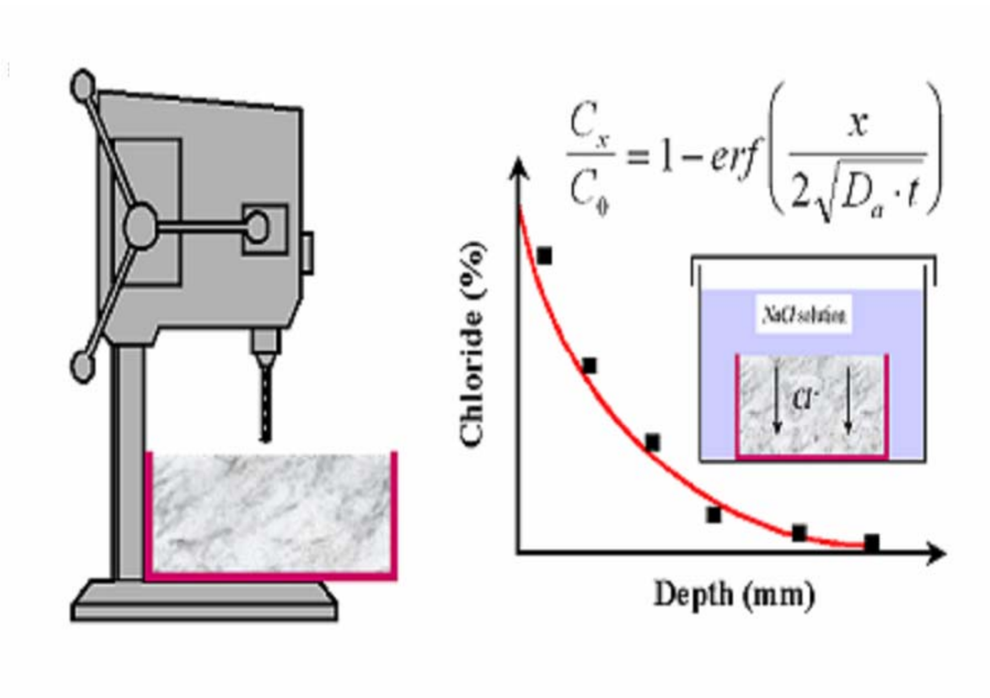

Fig. 4 Experimental procedure in NT Build 443 test

3.2.4 NT Build 492

A potential of 10-60 V is applied across the concrete specimen for 24 hours to accelerate the velocity of migration of chloride ions. Then splitting the specimen and measuring the penetration depth of chlorides by using a colourimetric method. Test set-up is shown in Fig. 5.

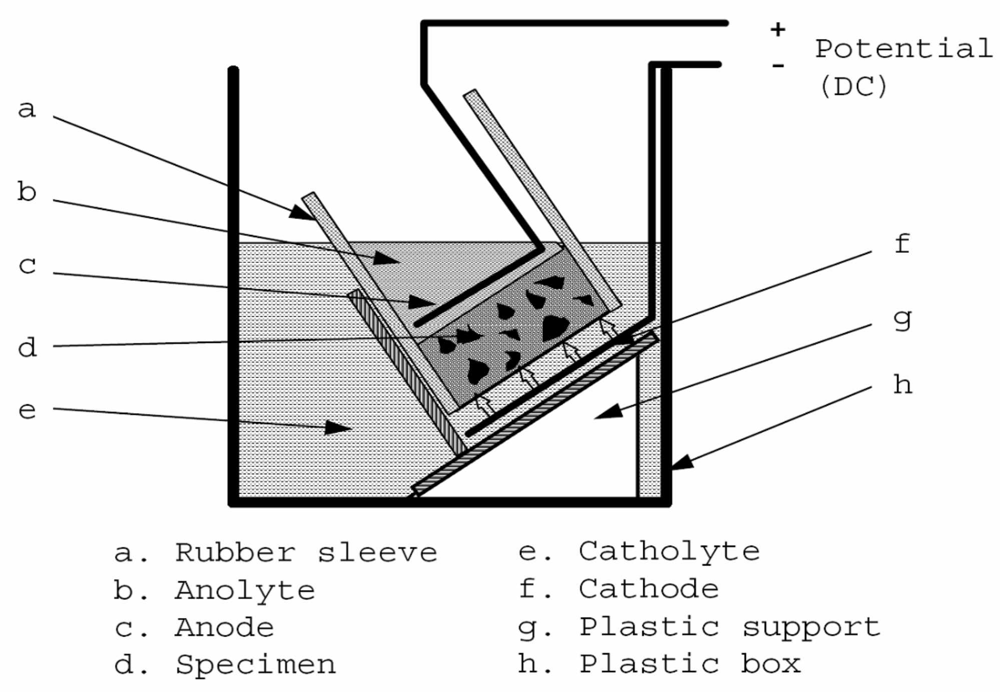

Fig. 5 NT Build 492 test arrangement

4. RESULTS AND DISCUSSION

4.1 Comparison of Diffusion Coefficients Predicted by standard Nordtest Methods with ACI Model

Diffusion coefficients measured from four test methods as stated above for concrete of each mix at an age of 28-days are compared with that from ACI (Life 365) model including the ratio of water and binder, and mineral admixtures. Those are shown in Fig. 6. In Fig. 6, test method of ASTM C 1202 is excluded because it is not an estimation quantified based on the total Coulombs. NT Build 355, NT Build 443, and NT Build 492 are compared only if quantitative values are provided. As shown in Fig. 6, the magnitude of diffusion coefficients can be written as NT Build 492 ≒ NT Build 443 ≫ NT Build 355.

Diffusion coefficient by NT Build 355 is quite low compared with those by NT Build 443 and NT Build 492 considering the age of concrete specimen (28 days). It is about 1/8 ~ 1/10 of those by NT Build 443 and NT Build 492.

The most similar test method to the real condition is NT Build 443 which is immersion test and apparent diffusion coefficient cab be calculated. But, this test method takes too long, that is, 28 days for curing and 28, 90, and 180 days for immersion. And, also the chloride profile by grinding the specimen by 2mm slice successively from the exposed surface. From the above results, the diffusion coefficient is determined by regression analysis. This procedure is too long and needs high expertise.

NT Build 492 takes 24 hours which is relatively short and measuring procedures are simple. So, this seems to be proper to the criteria to control quality by diffusion coefficient. And, this is adopted in Duracrete model in Europe to estimate the diffusion coefficient. Time dependency of the diffusion coefficients by ages of concrete specimen can be determined properly using NT Build 492.

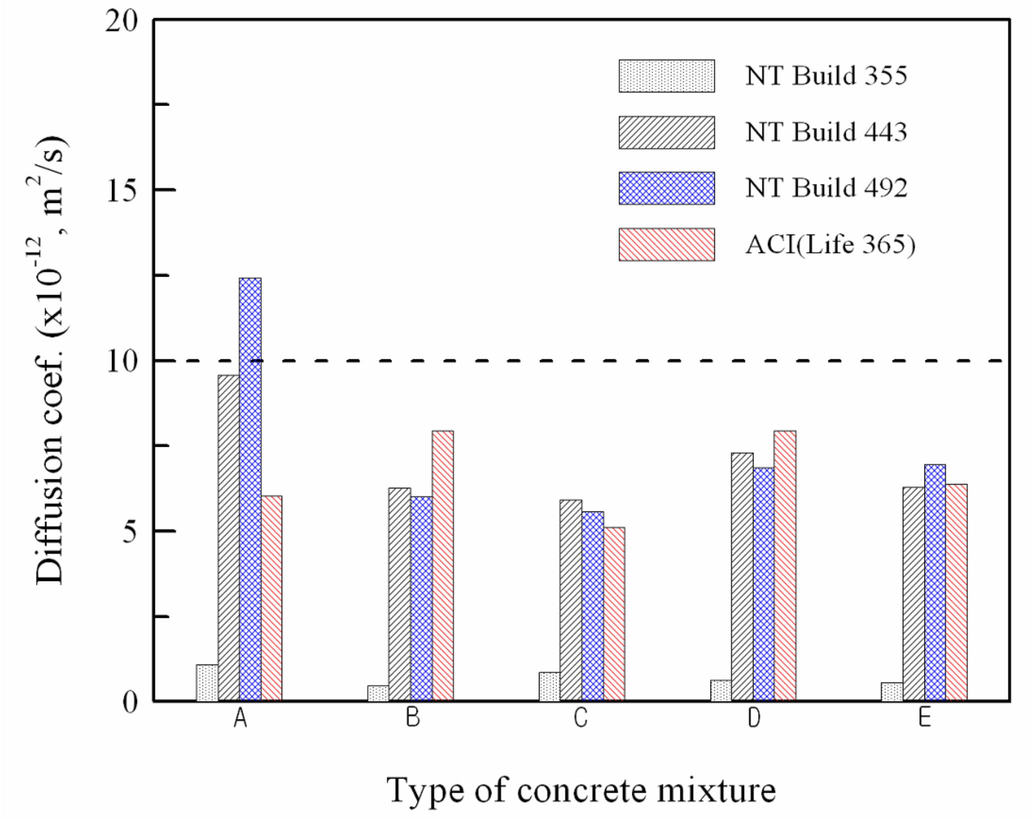

Fig. 6 Diffusion coefficients of concrete mixtures according to various methods

4.2 Comparison of Diffusion Coefficients by Immersion Test with by Criteria Test

Test results by NT Build 443 (immersion test) which is the most similar to the real condition and NT Build 492 are plotted in Fig. 7(a). In Fig. 7(a), mix A that characteristics of mix is different from the others is excluding. Relationship of the diffusion coefficient from immersion test and that by penetration depth is good as shown (R^2 = 0.88). Test results by NT Build 443 (immersion test) and the predicted values by ACI (Life 365) model are plotted in Fig. 7(b) to decide the criteria of diffusion coefficient for quality control. And, also the predicted values by ACI (Life 365) model and test results by NT Build 492 are plotted in Fig. 7(c). Relationship of the diffusion coefficient from immersion test and that by the predicted values by ACI (Life 365) model is fairly good as shown (R^2 = 0.89) in Fig. 7(b). Test results by NT Build 443 (immersion test) are larger than the predicted values by ACI (Life 365) model by about 10%. It also can be seen in Fig. 7(c) that relationship of the predicted values by ACI (Life 365) model and test results by NT Build 492 is good as shown (R^2 = 0.88). From the above test results, NT Build 492 can be concluded as a test method for criteria of quality control of chloride diffusion coefficient.

The criteria of diffusion coefficient for quality control have been determined based on the above test results. Test frequency is once per 1000 m^3 (or once per day when production of concrete exceeds 1000 m^3) and 3 specimens are used for each test. If test results using specimens at age of 28 days are failed, test has to be conducted at 60 days or 90 days. If test results at 60 days or 90 days are passed, then those results are satisfied. If not, a proper protection has to be prepared such as coating, etc..

Based on the above guidelines, the intermediate test results of marine concrete bridges for quality control against chloride attacks are summarized in Table 3. All of the test results are satisfied with the criteria, and reliability is also fairly high as coefficient of variation is about 10%.

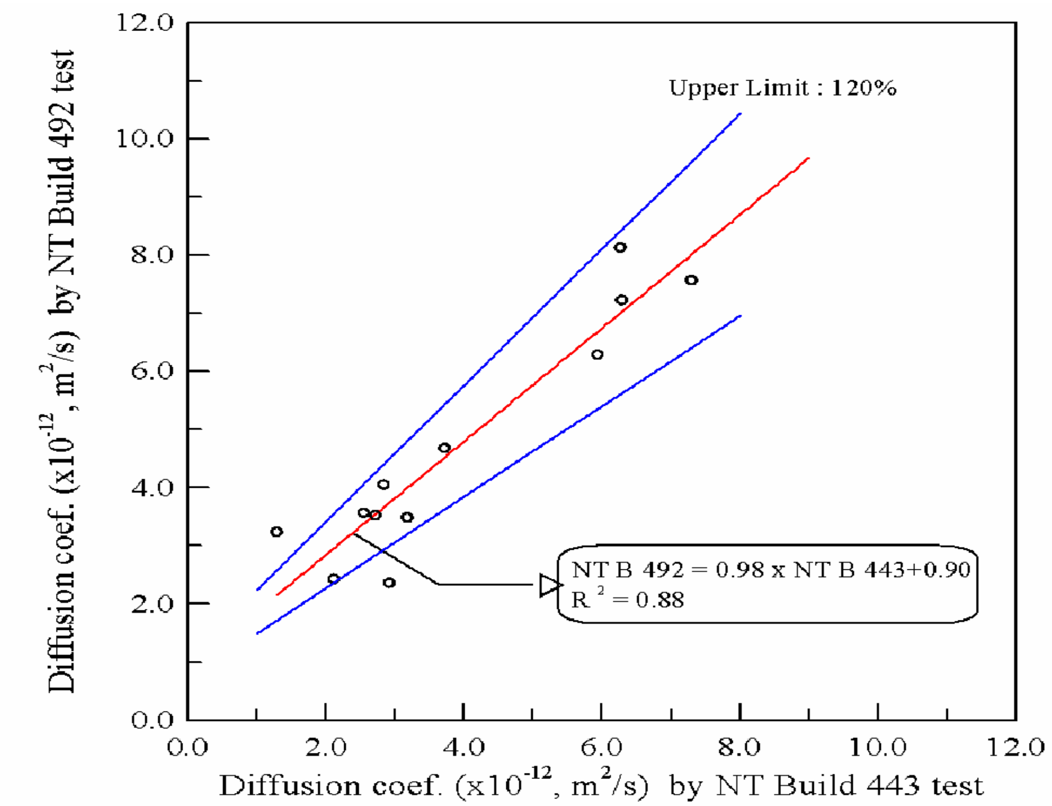

Fig. 7(a) NT Build 443 versus NT Build 492 method

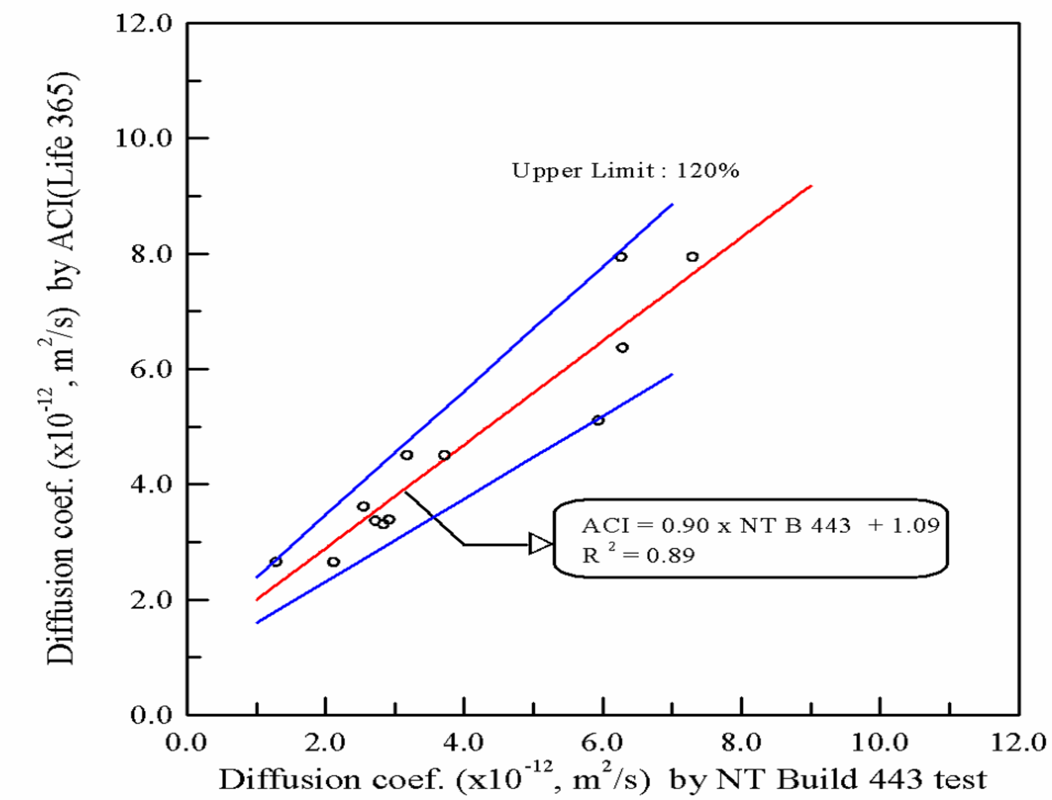

Fig. 7(b) NT Build 443 versus ACI(life 365) method

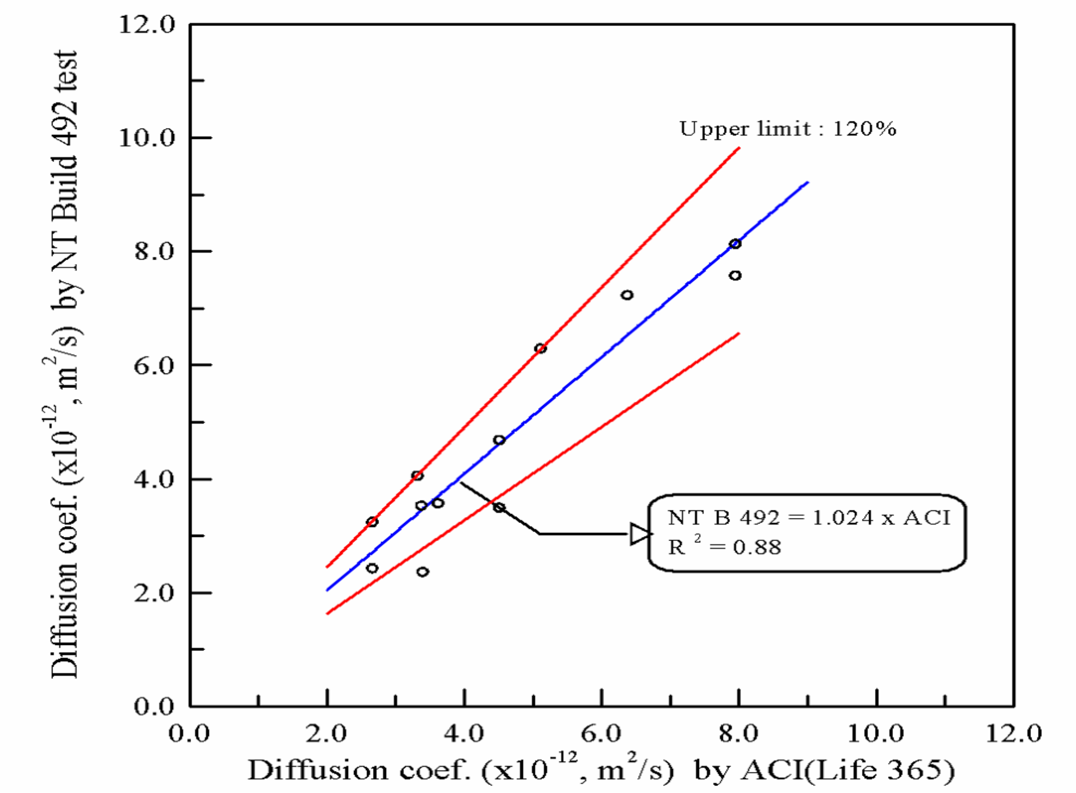

Fig. 7(c) ACI (life 365) versus NT Build 492 method

Table 3 Results of quality control test for assuring the durability of concrete against chloride attack (utill 2008. 5)

Construction field name / Design comp. str., MPa		Execution number	Criteria of diffusion coefficient($\times 10^{-12}$, m^2/s)	Average value of test results ($\times 10^{-12}$, m^2/s)
A site	40MPa	13	11.80	6.69
A site	35MPa	9	8.14	6.34
B site	40MPa	32	6.30	4.99
B site	35MPa	17	7.58	5.41
C site	40MPa	4	6.30	4.74
C site	35MPa	34	7.58	5.43
D site	40MPa	3	7.24	4.53
D site	35MPa	1	7.23	6.65

5. CONCLUSIONS

Corrosion induced primarily by chloride ingress and diffusion, deteriorates concrete structures exposed to aggressive agents, such as chloride, significantly. Therefore, chloride attack should be included to estimate durability and design of concrete structures. The diffusion coefficient chloride ions in design should be maintained during construction of concrete structures. The criteria test of quality control of chloride diffusion coefficient for each concrete mix has been proposed based on the relationship of the accelerated tests and immersion tests, because it is very difficult in real fields.

By the proposed method, quality control of concrete used in the approaching road of Incheon Bridge has been conducted to provide 100 years of life span. Further study of the frequency of tests, etc. is needed.

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